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Torrefaction of wheat and barley straw after microwave heating

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HIGHLIGHTS

- Microwave irradiation was used for the torrefaction of wheat and barley straw.
- Barley straw tended to carbonize more than wheat straw under microwave irradiation.
- Energy density increased in both wheat and barley straw after torrefaction.
- Biomass grindability and hydrophobicity improved significantly after torrefaction.

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ABSTRACT

Microwave irradiation was used in this study for the torrefaction of wheat and barley straw. The torrefaction effect was studied by varying the microwave power level (200–300 W), reaction time (10–20 min) and moisture content of biomass (5–15%). Mass yield and energy yield of the torrefied biomass was determined. Fuel properties like H/C and O/C ratio were assessed from elemental composition. Grinding characteristics and hydrophobicity of the torrefied sample were studied and compared with the raw biomass. Barley straw tended to carbonize more under microwave irradiation with 29.1% increase in the C content against 16.2% in the case of wheat straw when torrefied at 300 W for 20 min. Both H/C and O/C ratio decreased with increase in power and reaction time. The energy density increased by 14–15% in wheat straw and 21–23% in barley straw under suitable reaction condition. Mass and energy yields were 64.0–97.8% and 73.8–98.4%, respectively for wheat straw. In barley straw, mass and energy yields were 42.7–97.4% and 52.5–97.3%, respectively. Moisture content of the biomass did not affect the reaction as much as other parameters and the mass yields were comparable between different moisture contents. Grindability of the biomass improved significantly after torrefaction. The particle size ratio between torrefied and untreated straw after grinding was 0.66 and 0.61 for wheat and barley, respectively. The torrefied biomass was more hydrophobic and the moisture uptake was reduced by 61–68% under suitable torrefaction condition. Microwave irradiation can be used effectively for torrefaction of the two biomass investigated at moderate power and short process time.

1. Introduction

In recent years, biomass has been sought after as a major source of renewable energy. Biomass is a source of sustainable carbon–neutral energy and has potential to play an important role in the future. Biomass is by far the most important source of renewable energy today, accounting for about 10% of total primary energy use and 78% of total renewable energy [1]. Among all the types of biomass sources, agricultural residues are the most promising in terms of their abundance and non-association with the food versus fuel problem [2]. Many agricultural residues are poorly utilized and often burnt in open fields causing massive air pollution. However, these valuable resources can be converted to green chemicals and biofuels with the use of suitable technologies. There are many thermo-chemical conversion technologies, including carbonization, torrefaction, pyrolysis, and gasification, that have been researched and developed to treat agricultural waste [3]. The products of these methods can be further upgraded into various useful biofuels to generate heat and electricity [4].

Untreated biomass materials are known to possess certain disadvantages such as high water content, hydrophilic nature, low calorific value, low energy density, poor grindability, high transportation cost due to high bulk, low combustion efficiency, and thermal instability during combustion because of high oxygen content. Torrefaction is one of the pretreatment methods which can address most of these inherent issues and upgrade untreated biomass to a higher quality and more attractive biofuel [5].

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Torrefaction is a relatively mild thermo-chemical treatment of biomass carried out at low temperature range of 200–300 °C at atmospheric pressure under inert atmospheric conditions. The heating rates are usually kept below 50 °C/min [4]. It helps to remove water and low-molecular-weight organic volatiles and converts biomass materials into high quality fuels with low water content, low O/C ratio, and high energy density. It makes the biomass brittle and improves its grindability [6–8]. Furthermore, torrefied biomass can be utilized as a solid fuel for home or industry use. It can also be co-fired with coal in a pulverized coal-fired boiler [9]. Torrefied products are hydrophobic, which makes them convenient for storage and transportation [10]. Moreover, high energy torrefied pellets can also be made from torrefied biomass [11].

In recent years, there have been several studies on the torrefaction of biomass. Most of the studies used electric heating (conventional heating method) as the heating source and the effects of process temperature and process time on torrefaction of biomass were discussed [12–16]. In general, conventional heating-based torrefaction requires longer processing time. In conventional heating, energy is transferred to the material through three modes viz., conduction, convection, and radiation from outside to the inside of the biomass. However, microwave irradiation provides an alternative method of heat transfer in addition to these three heat transfer modes. Its frequency is usually in the range of 300 MHz and 300 GHz with corresponding wavelength between 1 m and 1 mm, respectively. Not all materials can absorb microwaves. According to the interaction with microwaves, materials can be classified into three types: insulators (transparent), conductors (reflective), and dielectrics (absorptive). Therefore, microwave heating can be regarded as dielectric heating. Heat is generated by the molecular rotation and friction induced by microwave radiation. Because of the difference in how heat is being generated, microwave heating has many potential advantages in processing materials. Additionally, microwave heating provides shorter reaction time, accurate control, prevents undesirable secondary reactions that lead to formation of impurities, and provides volumetric heating with good penetration depth [17,18]. Microwave heating is a selective, rapid, uniform, and energy-saving method without direct contact with the heated material [19]. However, more polar components will absorb more energy, and thus, “hot spots” will be created in non-homogeneous materials like biomass. It is hypothesized that this unique heating feature results in an “explosion” effect in the particles and improves the disruption of the lignocellulosic structures [2].

Microwave technology has been applied for various purposes, such as chemical synthesis, digestion, extraction, drying, cooking, and pyrolysis, [4,20]. Microwave induced torrefaction of some biomass like rice husk and sugar cane residue [20], rice straw and Pennisetum [4], sugarcane bagasse [21] and corn stover [22,23] have been reported in the last few years. In these studies, the effect of different experimental conditions viz., microwave power level, processing time, biomass particle size and water content of biomass on torrefied biomass characteristics and reaction kinetics have been investigated. Yemis and Giuseppe [24] optimized the acid-catalyzed conversion conditions of wheat straw into furfural, 5-hydroxymethylfurfural (HMF), glucose, and xylose in a microwave assisted process using response surface methodology. Budarin et al. [25] investigated the low temperature microwave activation of wheat straw as a novel, energy efficient route to bio-oils and found that the properties of the bio-oil produced in terms of water content, elemental composition and calorific value have all been comparable to and in many cases better than conventional pyrolysis oils. They also observed that the use of simple additives, e.g. HCl, H_2SO_4 and NH_3, affected the process product distribution, along with changes in the chemical composition of the oils. Zhao et al. [26] studied the pyrolysis of compressed wheat and corn straw bale in a self-designed and built microwave heating device. The electricity consumption was between 0.58 and 0.65 kW h (kg straw)$^{-1}$ and with the increase of microwave power, the electricity consumption required for pyrolysis of unit mass of straw increased. Uneven heating was observed due to low penetration depth of microwave and large size of biomass sample. Wheat and barley straws are two abundantly available agricultural straws, which can be suitably treated for fuel use through torrefaction. Information on the torrefaction of these straws in microwave heating and the characteristics of the torrefied biomass is apparently missing in literature.

The objective of the present research is to investigate the process of microwave induced torrefaction of wheat and barley straw at different experimental conditions viz., microwave power level, reaction time and raw biomass moisture content. In addition, the effect of microwave torrefaction on the characteristics of torrefied products, grinding performance, and hydrophobicity was determined.

2. Material and methods

2.1. Crop residues

Wheat and barley straws in square bales were obtained from an experimental farm near Saskatoon, Saskatchewan, Canada. The initial moisture content of straw was determined by oven drying about 25 g samples in triplicate at 103 ± 2 °C for 24 h and found to be 5.1% (wb) for wheat and 5.8% (wb) for barley. The straws were ground by a hammer mill (Serial No. 6M13688; Glen Mills Inc., Maywood, NJ) using a screen size of 3.2 mm. A dust collector (House of Tools, Model No. DC-202B, Saskatoon, SK) was connected to the outlet of the hammer mill to control dust during operation, provide flowability of chopped biomass through the hammer mill, and collect the ground biomass. A Ro-Tap sieve shaker (W.S. Tyler Inc., Mentor, OH) and U.S. sieve numbers 16, 20, 30, 50, 70 and 100 (sieve opening sizes: 1190, 841, 595, 297, 210 and 149 μm, respectively) were used for the particle size analysis. About 100 g of the sample was taken in triplicate and placed on the top sieve and shaking was done for 10 min. The mass retained on each sieve and the bottom pan was determined and the geometric mean particle diameter was calculated in accordance to ASAE standard S319.3 [27]. The mean geometric particle size of wheat and barley straw grinds were 0.858 ± 0.001 mm and 0.873 ± 0.004 mm, respectively.

The raw biomass was conditioned to the desired moisture content of 10% (db) and 15% (db) by spraying water uniformly into the straw grinds. The wetted material was placed in a plastic bag and stored in a controlled environment chamber at 4 °C for one week for moisture equilibrium prior to experiments. The proximate analysis of the straw grind was carried out in accordance with ASTM Standard D3172 [28]. The ultimate analysis was done using an elemental analyser (Elementar-Vario EL III, Germany). Prior to fiber analysis, moisture and dry matter content was determined in triplicate by AOAC standard method 930.15 [29] by drying about 2 g of the samples at 135 °C for 2 h. Lignin content, ADF and NDF were determined as per ANKOM methods 8, 5 and 6 respectively [30–32] on a dry matter basis in duplicate. Cellulose content was calculated as ADF minus lignin content and hemicellulose content was calculated as NDF minus ADF. The higher heating values (HHV) of the straw samples were calculated from their C, H and N contents in a dry basis, using the following expression, as derived by Friedl et al. [33], for biomass from plant origin with a correlation coefficient of 0.935 between experimental and predicted HHV values.

$$\mathrm{HHV} = 3.55 \times \mathrm{C}^2 - 232 \times \mathrm{C} - 2230 \times \mathrm{H} + 51.2 \times \mathrm{C} \times \mathrm{H} + 131 \times \mathrm{N} + 20600 \qquad (1)$$